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Smart-grid investments, regulation and organization

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HIGHLIGHTS

- We review regulatory solutions for smart-grid and DER investments.
- What matters more than upfront incentives is organization and delegation.
- We model regulated investment under private information by a generator or a DSO.
- Highest welfare for high-powered incentives and centralized information.
- Market approaches likely to give poor outcomes for this case.

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ABSTRACT

Grid infrastructure managers worldwide are facing demands for reinvestments in new assets with higher on-grid and off-grid functionality in order to meet new environmental targets. The roles of the current actors will change as the vertical interfaces between regulated and unregulated tasks become blurred. In this paper, we characterize some of the effects of new asset investments policy on the network tasks, assets and costs and contrast this with the assumptions of the current economic network regulation. To provide structure, we present a model of investment provision under regulation between a distribution system operator and a potential investor–generator. The results from the model confirm the hypothesis that network regulation should find a focal point, should integrate externalities in the performance assessment and should avoid wide delegation of contracting-billing for smart-grid investments.

1. Introduction

Climate change policy in the post-Kyoto world has deep repercussions on the way we extract, produce, transport and consume natural resources in everyday life. Achieving a common aggregate goal by efforts in multiple countries, sectors and over generations is itself a daunting task for the world's governments, doing under uncertainty about the optimal path to achieve the target or even consensus about the strategic arbitrage between inter-temporal welfare and final environmental state is even worse. In this paper, we highlight a necessary but not sufficient condition for the deployment of enabling investments on the grid: an effective and coordinated regulation between grid operators and users.

The policy relevance of defining an adequate regulatory framework for the new grid operations cannot be understated. According to Aalbers et al. (2011), network operators face large investments in the nearby future. The magnitude of these cumulated investments is considerable, in the order of 40,000 MEUR in EC (2010)[1] up to 80,000 MEUR[2] in Woods and Gohn (2011), just for Europe 2010–2020. In the European context, a large part of this investment budget will have to raised through regulated tariffs, subsidies from national or regional taxes or by government-backed bank financing. Given the economic climate and the overall impact of energy prices on social welfare, it is evident that this surge in infrastructure investments will not pass unseen by end-consumers; private, commercial and industrial clients. It is therefore of primary policy importance to find regulatory models enabling these large and urgent investments while credibly assuring tariff-payers that the cost increases do not represent higher rent-taking from the firms and operators in the supply chain. Whereas most current literature, e.g. Niesten (2010)

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[1] Smartgrid investments in European transmission and distribution networks 2010–2020. Overall investment need in energy infrastructure is estimated to 142,000 MEUR in EC (2010).

[2] Transmission and distribution network investments.

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and Aalbers et al. (2011) focuses primarily on the relation between price regulation and investments in the network, we put an emphasis on the interaction between agents such as the regulator, network company and energy producer involved in investments. We believe that this aspect is especially relevant for the smart-grid infrastructure investments as these are justified also by significant off-grid benefits related to the final client, the energy supplier (retailer) and non-grid IT-providers (fixed and mobile telecommunications networks, cable-TV and multi-utilities). In a situation with evolving technologies and different system solutions, the regulator may find it more relevant to find a solid answer to the question *who* should invest rather than *what* should be authorized. In an information-economic framework, this implies a shift from the classical regulatory paradigm where the task is well specified and uniquely assigned to one agent, to a situation where the multiple agents may undertake a task with private costs and benefits.

The contributions of this paper are threefold. From a positive viewpoint, the paper provides an original analytical framework for explaining the lag in investments as well as the high costs for smart-grids implementations. The analytical model is based on standard principal agency theory. Our contribution here is that we have analyzed the investment effects of alternative organizations in a formal incentive framework, and that we have managed to gain interesting insights using only simple assumptions and relatively straightforward analyses. Finally, the energy policy contribution lies in the new structure for analyzing the optimal organization and regulation of smart grid investments, where most prior work either merely assumes that higher investment allocations would suffice, or assumes that competitive extension-bidding could achieve first-best results.

The outline of the paper is as follows: In Section 2 we define closer the 'smart grids', the network operations, conventional network regulation, followed by a review the existing literature on regulation of smart-grid operations and investments. In Section 3, we formulate a short conjecture for the inadequacy of the existing policy to meet the new needs. To address the issue normatively, we present a multi-level agency model under asymmetric information in Section 4, for which we derive results in both closed form and easily accessible graphical representations in Section 5. The paper is closed with a policy discussion in Section 6.

2. Smart grids and network regulation

The regulators retain the following definition of smart grids

> [A] Smart Grid is an electricity network that can cost efficiently integrate the behavior and actions of all users connected to it generators, consumers and those that do both in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety. ERGEG (2009, p. 12).

It is indicative that the preferred definition basically is a restatement of the definition of the Smart Grids European Technology Platform with two additions; *cost efficiently* and the specification in the latter part to be *economically* [efficient].

Notwithstanding the somewhat diverse definitions, there is some consensus regarding the scope of smart grid operations. The smart grids operate in six priority areas: (i) optimization of grid operation and utilization, (ii) optimization of grid infrastructure, (iii) integration of decentralized energy resources, (iv) enhanced ICT services on the grid, (v) active distribution grids, and (vi) new markets and end-user services, e.g. for control of load and decentralized generation. Pepermans et al. (2005) list as driving forces for the introduction of decentralized, flexible and diversified energy services, such as (i) standby or peak use capacity (peak shaving), (ii) reliability and power quality, (iii) substitute for investments in grid expansion, (iv) ancillary services, and environmental concerns, i.e. (v) cogeneration CHP,[3] and (vi) efficient use of inexpensive energy resources.[4] The policy issues are summarized as (i) high financial cost, (ii) limited choices of primary fuels, (iii) lower economic efficiency (primarily allocative efficiency), (iv) inefficient fuel utilization from an environmental viewpoint, (v) lower supply security, (vi) mixed power quality (system frequency, voltage level, change in power flow, reduced effectiveness of protection equipment, reactive power, power conditioning).

The reduction of carbon emissions is result of three complementary actions on the supply side: changes in fuel mix, shifts in generation technology and carbon capture and storage (CCS). We leave the latter part until the last section, thus addressing the decarbonization of the electricity sector through fuel and technology mix. The fuel choices are to be guided through an appropriate implementation of pricing mechanisms for the externalities related to CO_2-emissions, such as European Emission Trading System (ETS) or equivalent, which lie beyond the scope of network regulation. The electricity generation park is planned to be extended substantially with renewable energy resources (RES), primarily wind, tidal power, biomass and photovoltaic (PV) generation, cf. EC (2006, 2009a,b,c). The greatest absolute and relative increase among RES is found for windpower from 82 TWh produced in 2006 to 545 TWh planned[5] in 2020 EC (2006). The new RES will be smaller units than the current centralized plants as a consequence of exhausted locations, local NIMBY[6] resistance, diminishing returns in resource availability and lower economies of scale for certain technologies. In particular for wind and solar, the lion's part of the increase will be made as distributed generation (DG), i.e. installations below 100 MW connected directly to the distribution network. For photovoltaic in Europe with the exception of Spain and Portugal, the installations are residential micro-generators connected directly to the low-voltage grid and used mainly for autoconsumption.

The load in the smart grid is partially controlled by demand-side management (DSM) mechanisms that control interruptible loads, schedule consumption and charge local energy storages (vehicles, heat storage) with respect to local DG availability, real-time price signals from the wholesale markets and local demand signals. The term we use below for both decentralized generation and load-side management is Distributed Energy Resource (DER). In combination with energy efficiency applied to both residential, commercial and industrial load, the overall energy volume transported per customer is expected to decrease. However, with continued expansion of total power for household and commercial appliances, the peak load is likely not decreasing, or at least less than the total energy consumption.

2.1. Conventional network regulation

The guiding principle for all economic activity in the Western society is the *market*. Network operations, such as distribution of electricity or gas, are examples of natural monopolies or market failures. For electricity distribution, the monopoly is accentuated by (i) the existence of a single supplier of the service for each

[3] Combined heat and power production.

[4] Note that the energy sources often are free (solar energy, tidal, wind) or even negatively priced (waste, industrial heat).

[5] Green-X model, least cost scenario in EC (2006).

[6] Acronym for *Not In My Backyard*, opposition regarding land use by neighbors and/or their representatives.

customer, (ii) no substitute for the offered service and very low price elasticity, and (iii) high economic and legal barriers to market entry due to the asset-specificity and its essential importance for societal welfare. Without non-discriminatory access to the infrastructure, the operator's potential rent extraction could distort incentives for generator investments, retail competition and market efficiency, leading to losses in allocative efficiency. Without vertical separation, the network operator–generator could moreover directly distort competition by not only distorting access to information and infrastructure, but potentially also cross-subsidizing the competitive business by the monopoly operations. Moreover, the vertical separation (*unbundling*) of the energy sector in Europe is also instrumental to the implementation of modern incentive-based regulation.

An authoritative reading in the theory of incentive regulation is Laffont and Tirole (1993). Contemporary economic theory pursues the private goals and strategic behavior of the individual agent, with particular emphasis at the access, cost and use of information. The practical applications from this stream of research have had a profound impact on modern markets, market instruments, contracts and economic restructuring. The fundamental aspect that is relevant to the discussion in this paper is the family of regulatory models shown to be optimal for the case of asymmetry of information regarding operator cost, effort and demand potential. The results for so called *high-powered regulation* where the firm becomes residual claimant of (at least part) of the difference between *ex ante* approved revenue and *ex post* realized cost confirm those of actual implementations, such as the seminal RPI-X model by Littlechild (1983). The model is robust for technology changes and productivity progress as long as the output specification is stable and exogenously given.

However, as the discussion regarding smart-grid investments primarily is focused on the promotion of new investments, it is clear that the European predominant regulatory model of revenue- or price-caps, is challenged in its fundamental assumptions. As discussed in e.g. Meeus et al. (2010), the current regulation is inadequate in the sense that (i) absolute cost containment is infeasible (since the costs will increase), (ii) the standard revenue-drivers (e.g. energy transported) will generate lower income to the operators (intrinsic in the energy efficiency component of the smart grid), and (iii) that explicit incentives are weak or ineffective for activities such as smart-grid development and coordination.

As a resort, some regulators then implement separate non-market solutions (feed-in tariffs, priority dispatch, investment subsidies, connection privileges, etc.) to accelerate or, in general, implement low-carbon technologies. As we will argue, in agreement with Pollitt (2008), these "intuitive" solutions are not only philosophically inconsistent with the market paradigm, they also increase complexity for actors, regulatory uncertainty and sometimes imply distortions on both allocative and technical efficiency. Next, we will define the typical roles for the operators in an unbundled European setting.

2.2. Typical European network operations before smart grids

The energy system is from an economic-judicial viewpoint seen as consisting in generation (production of energy), transmission,[7] distribution,[8] supply[9] and customers (load). The directive defines specific roles for the single[10] national transmission system operator (TSO) versus the distribution system operators (DSOs). The TSO is distinguished from the DSOs both in terms of scope of task (power system responsibility vs. local supply services), but also in terms of asset base. However, the European directives do not specify the voltage levels, leaving the actual separation to the national legislation. *De facto* this introduces a certain heterogeneity among the TSOs,[11] responsible for networks from 220 kV (Spain, Sweden), 132 kV (UK, Denmark), 110 kV (the Netherlands), 63 kV (France) down to 26 kV (Belgium).

The European energy market directives prescribe successively stricter vertical separation. Whereas the first directive 96/92/EC, EC (1996) merely imposed distinct management functions for the TSO and accounting unbundling for TSO and DSOs, the second directive 2003/54/EC required management unbundling also for DSOs and controls for the operational independence of the TSOs and DSOs, if subsidiaries of other firms. In the third directive 2009/72/EC full ownership unbundling is required for TSOs and the control independence of the DSOs is reinforced.

In addition, the RES Directive (2009/29/EC) explicitly stipulates (Art 16:3 and 5) that electricity TSO and DSO are obliged to disclose cost and benefit analyses with respect to the connection of renewable energy generation and that the residual costs are either shared among grid users (Art 6) with respect to a objective, transparent and non-discriminatory criteria (without stating those), or absorbed by the network operator (Art 4).

In a typical European grid, we thus find an active transmission system operator connecting the central generator to a 220 kV or 300 kV 'backbone' and a set of DSOs distributing electricity from substations 110–132 kV down to low voltage feeders. The latter operate primarily passive networks with relatively low visibility and control possibilities. Suppliers (retailers) are contractual agents selling electricity from the generators to the end-users, without any installed assets at neither the load side, nor the grid. Due to the vertical separation from generation and supply to transport, the DSOs have economic interest in new grid technologies only in sofar they contribute to lower network losses, limit the amount of non-invoiced electricity through improved metering, or postpone grid reinforcements in high-cost areas due to peak-shaving behavior from the clients. When it comes to advanced control of decentralized energy resources, distributed generation and potential participation of autoproducers in local markets for grid services, the current incentives are negative for DSOs, cf. Meeus et al. (2010).

In the next section, we will revisit the properties necessary for the overall European high-powered regulation model to work in this context.

2.3. Information access, task separability, independence and externalities

The properties of high-powered (incentive) network regulation depend on a number of factors, most importantly the asymmetry on cost information, task separability, role of independence and externalities Joskow (2006).

Given that the demand for network connection is virtually inelastic, at least for electricity, the natural orientation of the regulatory policy since deregulation has been to induce cost efficiency to limit monopoly rents from the distribution system operators (DSOs). For transmission system operators (TSOs), the task scope already included a number of elements with high externalities and cascade effects on welfare, such as the

[7] The transport of electricity on the extra high-voltage and high-voltage interconnected system with a view to its delivery to final customers or to distributors, but does not include supply, 2009/72/EC Art. 2:3.

[8] The transport of electricity on high-voltage, medium-voltage and low-voltage distribution systems with a view to its delivery to customers, but does not include supply, 2009/72/EC Art. 2:5.

[9] Sale, including resale, of electricity to customers. 2009/72/EC Art. 2:19.

[10] Exceptions from the outset in Germany (4) and until 2010 in Denmark (2).

[11] The introduction of a third regulated level in Norway and Sweden, the regional transmission operator (RTO) operating primarily transport services at 110–220 kV, is unique.

investments in market facilitation and security of supply in general, prompting the regulators to impose relatively low-powered initial regimes for capital costs[12] and operating expenditure[13] (Moens, 2009).

First, the cost information in a yardstick regime is related to access to a reference set of cost observations for structurally comparable operators (Agrell et al., 2005). For DSO, this condition is largely met in jurisdictions such as Germany (Agrell and Bogetoft, 2007), or Scandinavia (Agrell and Bogetoft, 2010) where data standardization and collection permit the use of econometric non-parametric models to calculate efficient costs with relatively high precision. For jurisdictions with a smaller number of operators, international datasets may potentially be used after correcting for cost and operating differences. However, the assumption of comparability relies on the previous assumption that tasks and cost drivers are uniformly applied across units, which limits the use of international data in an uncoordinated future.

Second, the current regulatory paradigm relies on high task separability between regulated segments. In the pre-Kyoto world of central generation and loosely interconnected systems, primarily for the purpose of supply security, the main network services are characterized by relatively high separability between the two vertical segments under regulation in the EU framework: distribution and transmission. Another challenge for task separability is the necessity to coordinate technical research and development activities in order to achieve effective and interoperable solutions to attract investments at the generation stage. Although assigned as an explicit responsibility for the TSOs (ENTSO-E tasks, Art 8 Section 3a and Section 5, EC 714/2009), we note that both regulators (OFGEM and NMa/EK) as well as DSO associations (Eurelectric) are implementing support schemes for DSO R&D.

Third, independence has been implemented primarily through unbundling of accounts for DSO, ownership unbundling only for TSOs to counter market power in generation, as discussed above. As we will show, this feature brings a lower rent extraction for the 'old-grid' distribution business, but it also comes at a cost as it blocks the internalization of certain benefits and costs for the smart grid.

Fourth, the externalities in the "old" world were mainly related to the TSO operations, both in terms of market functioning and environmental impact. The new situation, foreseeing wide integration of generation and load control in distribution will put the environmental externalities (CO_2, space, noise, heat) in the focus of the DSO. Without adequate means of internalizing part of these externalities, it is clear that the DSO will be lukewarm concerning investments and reluctant to carry regulatory and business risk.[14]

2.4. Prior work on smart grids and regulation

Brunekreeft and Ehlers (2005) address specifically the problem whether the unbundling of DSO changes the incentives for DG integration. One of their contributions is to introduce the temporal (short-run vs. long-run) perspective, questioning whether the DSOs are likely to experience reductions in network losses, as opposed to TSOs. Arguing that even high-powered regimes such as price- and revenue-caps for DSO in reality are regularly reset based partially on CAPEX estimates, the authors conclude that the DSO unbundling and incentive regulation are likely both to distort the timing, volume and types of DG investments made by DSOs. The results are compared to actual investment intensity among DSOs and the slow response to coordinated incentives DG–DSO.

Pollitt (2008) discusses the prospects for future network regulation, based on an ex post analysis of the UK regulatory development. Noting that most investments at both the electricity DSO and TSO level are driven by RES support schemes (such as Renewables Obligation Certificates, ROC, and the Transmission Investment for Renewable Generation, TIRG), Pollitt foresees general increases in electricity prices of about 10% to 15%. For the UK, the Stern review foresees a total investment need of 1% of GDP to meet carbon emission targets by 2050, thereof around 4000 MGBP for the electricity sector resulting in a 80% reduction of the CO_2 emissions by 2050. The establishment of the Office of Climate Change (OCC) in the UK must be seen as a rare and welcome sign of commitment from the political principals with respect to the climate change target policy, following a period of high uncertainty and slow progress from a very low level of RES penetration. In his prospective analysis of the requirements for new network regulation, Pollitt highlights four points: (1) maintenance of the key learnings from the liberalized energy market, (2) increased process focus in regulation, lower emphasis on end-user prices as indicator of regulatory effectiveness, (3) focus at the economic realization of climate change policy measures, such as interventions, pilot projects and support schemes, (4) effective management of regulatory and market risk through more sophisticated risk transfer instruments. Specifically, Pollitt outlines a new regulatory model with three elements:

First, delegation of investment decisions to negotiated settlements between grid operators and users. This change in the direction of output-based regulation transforms the relationship between the network operator and the regulator from ex ante centralized bargaining to ex post auditing. Positive experiences within OFGEM for gas distribution prices and a series of international experiences analyzed by Littlechild (e.g. Littlechild, 2002; Littlechild and Skerk, 2008) using negotiated access prices, investment decisions and quality norms support this argument.

Second, more extensive promotion of competition on the grid and for its expansion (tendered expansion). By carefully reviewing explicit and implicit barriers to entry as well as strengthen the ownership unbundling requirements down to DSO level, emerging competition may be facilitated for generation, energy services and heat networks.

Third, Pollitt discusses the lead role of the regulator in the climate change setting to make effective internalization of the CO_2 externalities, such as in the case of investment discounting (Weitzman, 2008), essentially acting as to assure the most economic implementation of the environmental externalities desired.

Woodman and Baker (2008) review the UK policy on DER, concluding that the current regulatory framework has been conceived to promote competition within a given energy resource, rather than the development of a more system response to socio-environmental objectives that could be addressed with DER. The recommendations for regulation focus at the removal of investment and connection barriers for DER, increased incentives for DSO participation through higher costs for losses and some alignment mechanism for investors-DSO investment decisions.

Green (2012) analyses the requirements for network regulation for three types of systems (or scopes of deregulation); retail competition (as in EU), wholesale competition (as in US and Latin

[12] Also called capital expenditure, CAPEX, including the depreciation of the regulated asset base as well as a weighted average cost of capital on the invested capital.

[13] Operating expenditure or OPEX includes the variable costs for operation, maintenance, administration, metering, billing and developing the network. In Europe, this amount is frequently subject to benchmarking through quantitative techniques, in the USA and elsewhere it is often estimated as a percentage of the capital costs.

[14] Deuse et al. (2005) discuss the risks of underinvestment in renewables and smart grids due to regulatory mechanisms that are inadequate, complex and lack long-term credibility for investors.

America) and integrated firms (potentially nationalized, e.g. the situation in France prior to 2005). Arguing that the low-carbon policy will give rise to higher capital expenditure per energy unit delivered, through remote locations, intermittent generation and non-coinciding peaks in load and generation for renewables.

Cossent et al. (2009) presents a thorough review of the state of actual national network regulation of DG in Europe and proceeds to give some regulatory recommendations. The recommendations include measures to provide economic signals for DG investors and instruments to be used in DSO network regulation. To provide efficient investment signals, Cossent et al. (2009) propose shallow connection charges and variable use of system (UoS) charges that are location-dependent, technology-dependent and cost-benefit reflective for the DG's impact on the DSO. Although the intention is to bring DSO-regulation closer to that of current TSO-regulation, including the strict unbundling from DGs, the recommendations are stay conceptual and urge for further research and development. In terms of network regulation, besides restating support for high-powered incentive regulation including the use of network service targets, the authors propose the ex ante allocation of investment budgets to DSOs with full delegation of the use of the funds. Ex post, the regulator should receive verifiable information about whether the investment has been carried out. The idea behind this proposal is to provide ''policy push'' from the regulator without the drawback of heavy-handed involvement in firm management. One of the model features in this paper investigates this regime. To promote investments in R&D by DSOs, Cossent et al. (2009) propose several possible means, such as activation with higher rates of return, partial pass-through of R&D expenses[15] and mechanisms to allow capture of efficiency gains from innovations during longer (several) regulatory periods.

Vogel (2009), analyzing the investment incentives for DG of high- and low-powered regimes, argues for deep connection charges as to avoid distortions up- and downstreams in the chain. However, the final conclusion is negative when taking into account monopoly power of the DSO, asymmetric information of cost and asset utilization, as well as the intrinsic difficulty to commit to ''true'' high-powered regimes without glancing at the asset base. Vogel (2009) concludes in this context that ''due to technical complexity of distribution grids and the manifold information asymmetries between the involved stakeholders, a proper design of deep charges will be very challenging to implement in to reality.'' The explicit instruction in the RES Directive to use shallow costs can then be seen as a recourse to a second-best solution in light of the problem. de Joode et al. (2009), observing that the cost impact of higher integration of decentralized generation is negative for passive DSO networks, recommend adaptation of the DSO regulation by means of operating expenditure adjustments and investment allowances.

Boot and van Bree (2010) reports on a wide range of policy issues related to a zero-carbon target in 2050, among those infrastructure for electricity. The authors highlight the investment consequence of low-carbon transitions into DSO networks that originally are constructed as passive networks. The role of new regulation in the view of Boot and van Bree (2010) is extended to issues such as locational pricing (also for DSO), long-term investment provisions, metering standards and innovation support. One approach forwarded in their report is the ''negotiated settlement'' proposed in Pollitt and Bialek (2008).

[15] The general decline of R&D expenditure in the energy sector, in particular among the network operators is discussed in Jamasb and Pollitt (2008).

3. Conjecture

We have argued, with some support from the rich literature on network regulation for low-carbon power systems, that the current paradigm will be partially outdated in the new world. However, rather than arguing along the classical Williamson range of hierarchy versus market as coordination instrument, we forward a relatively neglected stream of literature that could help to inform the theoretical foundation for future network regulation. Departing from the classical dyadic view of regulation as a two-party interaction (either regulator – firm or government – investor), the analysis above suggests that the old vertical separations between regulated segments, generation and load will be fuzzy and under continuous fire in the future. TSOs will need to understand DSO interactions, DSOs will need to operate local level control systems, intelligent load and distributed generation will call on both to control supply and demand of energy. Theoretically, the increased task complexity and asymmetry of information call for analysis of the interaction among the agents as a *team* rather than individually. Setting targets collectively increases the scope and probability that externalities can be exploited within the team, delegating the actions to the agents. Team theory also facilitates the analysis for collusive agreements among agents at various levels, both in terms of side-payments (market arrangements) and in terms of effort minimization. Indeed, the analysis of the collective team may also extend beyond the conventional frame firm-regulator and open interesting insights into the interaction and optimal organization of the multi-lateral regulatory structure itself.

Adopting the idea that network regulation may need to reconsider the boundaries and anticipate the overall effectiveness of a given policy for a societal goal, does not necessarily imply an abandon of the market as the governing principle for the energy sector also in the future. However, it does suggest that the *organization* and *delegation* of tasks to specific agents may be as important as the upfront monetary incentives offered to the agents themselves. This perspective is not very represented in the literature, with a notable exception of Joskow and Tirole (2005).

The rest of this paper contributes to the analysis of the future network regulation by deploying a simple, stylized model of joint investment under asymmetric information to explore the policy proposals forwarded with various arguments above. Jelovac and Macho-Stadler (2002) uses a more general formulation (of the complementary case) below. They assume that there is a probability function depending on the investment levels of high values being generated, and worked with complements in the sense that the probability function is increasing, concave and with positive cross derivatives. The model draws on the general agency literature on centralized or delegated contracting, cf. Mookherjee (1984, Mookherjee, 2006) for an overview. In the model below, documented in Agrell and Bogetoft (2011), we assume discrete investments and focus at the two extreme cases of perfect substitutes or complements. A variant of the model adjusted to the setting of decentralized health care provision is found in Bogetoft and Mikkers (2008).

4. Model

We present a formal model to investigate three prevalent scenarios as illustrated in Fig. 1.

The first scenario corresponds to a situation where the traditional unbundling requirement on the DSO is relaxed and where we allow the DSO to make direct investments in DER activities. The second scenario is a decentralized DSO scenario where the regulator contracts with the DSO and delegates the coordination

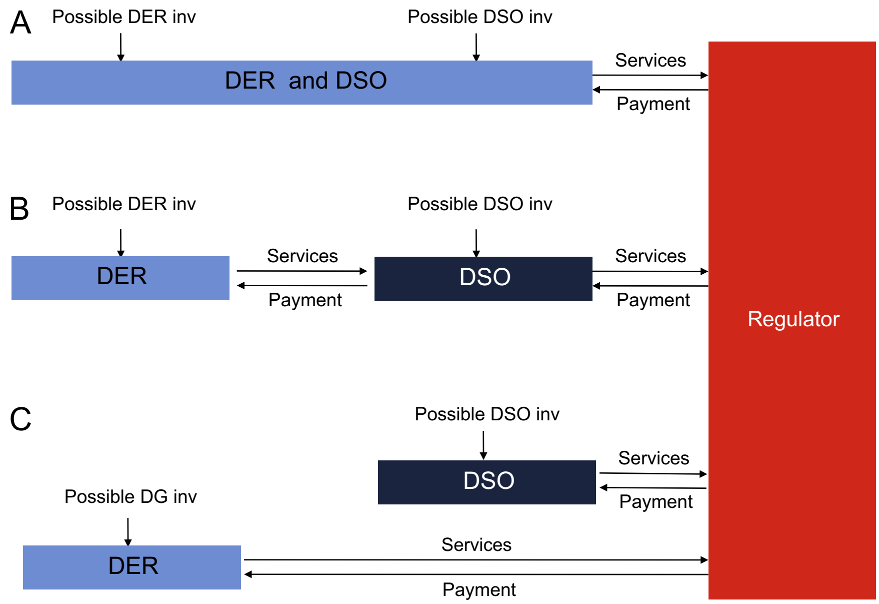

Fig. 1. DER investor, DSO and regulatory organization and delegation. (A) Integrated case, (B) Separate and decentralized incentives and (C) Separate and centralized incentives.

of DER investments to the DSO. The third scenario is again a decentralized scenario, only now the regulator coordinates the DER investments directly via centralized incentives.

The investment opportunities could involve investments in technologies, measurement equipments or protective devices and investments can be done by both the DSO and the DER. To simplify the exposition, we focus in this paper on the case of *complements*. This means that the social gains from investments are attained if and only if both DSO and DER invest. We note however that cases with substitute investments, i.e. where the social gains are generated if at least one of the actors, DSO or DER, invest, can be analyzed in a parallel manner. For more on such cases, see Agrell and Bogetoft (2011) and Bogetoft and Mikkers (2008).

4.1. Regulator

The aim of the regulator is to maximize social welfare. In a situation where new socially desirable investments are possible at the DER and DSO levels, respectively, we may assume that the extra value generated if these investments are undertaken is $V > 0$. This social value is known and verifiable, to abstract from the moral hazard problem of fulfilling investment obligations. If the regulator – as a representative for the consumers – has to pay a total transfer T as compensation to the DSO and/or the DER, e.g. by increasing the reimbursement (revenue-cap, etc.) or by direct investment subsidies, the social welfare improvement is

$$W = V - T$$

The objective of the regulator is to maximize the expected value of W.

4.2. Network operator, DSO

The network operator can make an investment at cost[16] $x > 0$ that is private information to the DSO. The DER and regulator only know that the DSO's cost – to make it simple – is independent from DER's cost, and that it follows a probability distribution with density $f(x)$ and cumulative probabilities $F(x)$. The aim of the risk neutral DSO is to maximize expected revenue minus costs, i.e.

$$E[R - I(R,x)x \mid x]$$

where R is the revenue that the DSO is paid.[17] It may depend on his investments as well as any other possible verifiable information, including the DER investments.

$I(R,x)$ is the (binary) investment decision of the DSO, one when investment is undertaken and value zero otherwise.

Lastly, we note that the expectation is a conditional one. It is the expected benefits given the private information about relevant investment costs.

4.3. Decentralized energy resource investor, DER

We model the investor,[18] denoted DER below, in an analogous manner. The DER can invest at a cost $y > 0$, which is his private information. The investment cost y follows a probability distribution with density $g(y)$ and cumulative probabilities $G(y)$, common knowledge to all players. The DER maximizes expected revenue[19] less cost, i.e.

$$E[S - J(S,y)y \mid y]$$

where S is the revenue paid to the DER. In case of a connection charge, S will be negative, and in case of net benefits from installing

[16] Cost is here seen as the effective net real annuity of depreciation and capital cost in an efficient capital market as to avoid burdening the presentation with the consideration of the actual investment pattern, taxation and life cycle maintenance pattern.

[17] The actual reimbursement scheme for the DSO through allowed tariffs, recognized performance in yardstick regimes, separate by-pass of investment costs or socialized transfers from other grid levels (transmission) is ignored here as only the behavioral effects are studied. Hence, we assume that the regulator enforces the same non-discriminatory financing pattern for this particular revenue as for any other DSO revenue, i.e. no additional distortion is introduced.

[18] The investor is here seen as either the client on the load side, or alternatively a service provider, e.g. a telecommunications provider that has an interest in a joint venture on the smart grids. However, the term *investor* should not be interpreted as a mere financial involvement, since we explicitly assume the agent to be a stakeholder in the network.

[19] Revenue corresponds to the case of a commercial downstream agent, such as the operator of a decentralized generation resource, an aggregator, a supplier or a telecommunications provider, but the model can be used without loss of generality for the case of a demand-side management (DSM) arrangement maximizing the utility of the load side.

the equipment, say by the private benefit exceeding the installation costs, the net costs y will be negative.

The binary investment strategy of the DER is $J(S,y)$. Whether to invest or not depends on the payment receives S and the cost of investment y.

5. Results

In the case of complements, the welfare effect V is obtained iff both agents invest, i.e. $I=1$ and $J=1$, else the outcome is normalized to zero.

The case could be illustrated by the coordination of smart meters, smart grids and demand side management (DSM) for e.g. automated load control. Installing the DSM without adequate metering and information transmission equipment will not improve social welfare. Likewise providing real-time information about grid usage and nodal prices in distribution networks without any load-side application is useless.

5.1. First best investments

The first-best solution requires the parties to invest as soon as their combined costs are less than the social value, i.e.

$$x+y \le V$$

The investment outcome is illustrated in Fig. 2. Investments must be undertaken in the lighter grey area and should be avoided in the darker grey area.

5.2. Integrated regulation

An integrated DSO–DER entity will consider its total costs of undertaking both investments

$$z=x+y$$

The regulator does not know these costs but expects that they have the cumulative distribution

$$H(z)=Prob\{Z \le z\}=\int_0^z G(z-x)f(x)\,dx$$

The best strategy for the regulator is, cf. e.g. Antle et al. (1999), to make a take-it-or-leave-it offer to the integrated entity. If the regulator offers z^*, the expected value for the regulator is

$$E(W)=[V-z^*]H(z^*)$$

The first order condition for an optimal offer therefore gives us the following result.

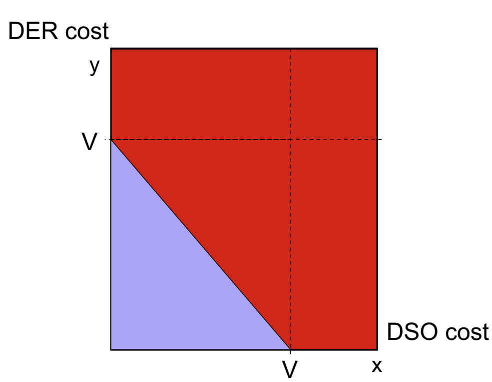

Fig. 2. DSO and DER investments, first-best solution.

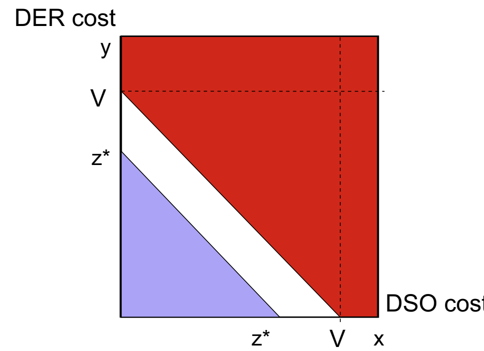

Fig. 3. DSO and DER investments, integrated solution.

Proposition 1. *The optimal regulatory contract with an integrated DSO–DER is to offer* z^* *fulfilling*

$$z^*=V-[H(z^*)/h(z^*)]$$

for the combined investment at the DSO and the DER level.

We see that *the regulator rations*, i.e. she offers less than the true value of the investment V. Her offer reflects the trade-off between lowering the information rents of the integrated entity and the probability of not having the investments at all. The investment outcome is illustrated in Fig. 3, where the white area denotes coordination losses, i.e. socially optimal investments that are not undertaken due to rationing.

Example 1. For the case $V=1$ and x,y following independent uniform distributions on [0, 1], we get $H(z)=z^2/2$ for $z \le 1$ and $H(z)=1-(2-z)^2/2$ for z in [1,2]. Following Proposition 1, the optimal investment threshold is $z^*=\frac{2}{3}$, i.e. investments take place only with probability $\frac{2}{9}$ whereas $\frac{1}{2}$ of the investments are socially desirable. Hence, the welfare loss corresponds to $\frac{5}{9} \simeq 56\%$ of the first-best investments.

5.3. Decentralized regulation

In the case of decentralized regulation, the regulator makes an offer to the DSO. The DSO then decides what to offer the DER level to invest. Assume again that the regulator offers z^* to the DSO for the combined investment. If $x > z^*$, no investment can take place since the DSO investment costs alone exceed the budget. If $x \le z^*$, the DSO can make an offer y^* to the DER investor. With probability $G(y^*)$, the DER will accept the offer. Therefore the DSO obtains y^* from solving

$$\max_y ((z^*-x)-y)G(y)$$

The first order condition for an inner optimum is

$$y^*=(z^*-x)-[G(y^*)/g(y^*)]$$

From the point of view of the regulator, this means that the regulator's offer z^* leads to DSO and DER investment only if both conditions $x \le z^*$ and $y \le y^*(z^*-x)$ hold. The first condition is satisfied with probability $F(z^*)$ and, for any given x, the second condition is satisfied with probability $G(y^*(z^*-x))$ by the independence of x and y. Therefore, the investment occurs with probability

$$H(z^*)=\int_0^{z^*} G(y^*(z^*-x))f(x)\,dx$$

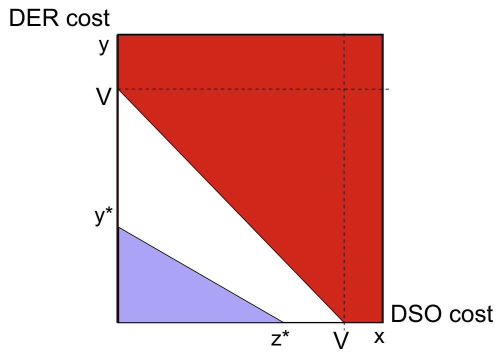

Fig. 4. DSO and DER investments, decentralized case.

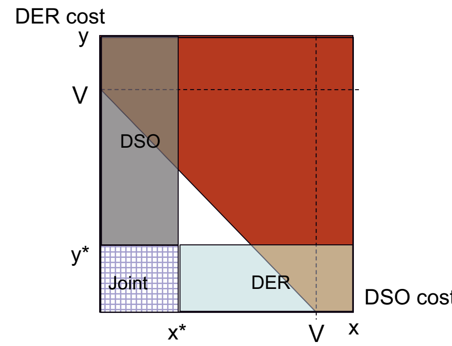

Fig. 5. DSO and DER investments, centralized independent case.

Proposition 2. *The optimal regulatory contract for the decentralized case is to offer the DSO z^* satisfying*

$$z^* = V - [H(z^*)/h(z^*)]$$

and to let the DSO contract with the DER.

The investment outcome in the decentralized case is illustrated in Fig. 4. We see that the regulator's desire to limit the DSO–DER information rents generally leads to under-investments. We also see that the DER effectively is rationed more harshly than the DSO. This happens because the DSO has to pass on information rents to the DER.

Example 2. For the case $V=1$ and x, y following uniform distributions on [0,1], we get $y^* = \frac{1}{2}(z-x)$ and thus $H(z) = z^2/4$ for $z \leq 1$. The optimal investment threshold is $z^* = \frac{2}{3}$, i.e. investments take place only with probability $\frac{1}{9}$. The social loss corresponds to $\frac{7}{9} \simeq 78\%$ of the first-best investments.

The negative outcomes above are robust also to the introduction of an optimal full revelation mechanism of Myerson (1979) type, since the competition among the agents is not effective when the participation of both agents is necessary.

5.4. Centralized independent regulation

We will close by investing centralized solutions where the regulator signs individual contracts with the DSO and DER. We first consider the simple case of independent contracts and next the more advanced and superior solution where the contracts are conditional.

In the independent centralized solution, the regulator makes offers x^* for the DSO and y^* for the DER as the solution to the problem

$$\max_{x,y}\{(V-x-y)G(y)F(x) - xF(x)[1-G(y)] - yG(y)[1-F(x)]\}$$

The first term represents the gain if both the DSO and DER accept the offer of the regulator. The second term represents the loss if the DER declines and the DSO accepts. This happens with probability $[1-G(y^*)]F(x^*)$. The third term represents the cost if the DER accepts and the DSO rejects the contract.

Differentiation w.r.t. x^* gives us the following first order condition:

$$G(y^*)[-F(x^*) + (V-x^*-y^*)f(x^*)] - [x^*f(x^*) + F(x^*)][1-G(y^*)] + y^*G(y^*)f(x^*) = 0$$

From this we get

$$y^* = G^{-1}\left(\frac{x^*f(x^*) + F(x^*)}{Vf(x^*)}\right)$$

and by symmetry, we get

$$x^* = F^{-1}\left(\frac{y^*g(y^*) + G(y^*)}{Vg(y^*)}\right)$$

The interpretation of the equations is that the regulator rations to lower information rents, and that she rations more she would with an individual agent to limit the risk only one party invests. The solution can be illustrated as in Fig. 5. We see that unless the regulator ration harshly, there is a considerable risk that one of the parties will invest while the other will not. Since the investments are complements, this is a very unattractive outcome.

Example 3. For the case of x, y following uniform distributions on [0,1], the first order derivatives of the objective function are $Vy-2x$ and $Vx-2y$, respectively. Thus, for $V=1$, optimal solution is $x^* = y^* = 0$. The social loss corresponds to 100% of the first-best investments! For $V=2$, the solution is arbitrary for any $x^* = y^*$ in [0,1] and for $V>2$ all investments are carried out.

The intuition behind the result for the centralized independent regulation lies in the unilateral commitment from the regulator to finance the investment irrespective of the coordination in the chain.

5.5. Centralized conditional regulation

To illustrate the possibility to get intermediate outcomes between those of full revelation and the centralized independent regulation we may a conditional regulation.

One possibility for the regulator is to offer the investment possibility to the DER investor and if he accepts and undertakes the investment, to offer the investment also to the DSO. The advantage of this arrangement compared to the individual regulations above is that we can avoid having the DSO invest without the DER investing. We can however not avoid that the DER invests but the DSO refuses to do so as well. The outcome following such an arrangement will therefore often be that the regulator should refrain from any investments to begin with much like in the case of individual regulation.

To get a different outcome, therefore, we will here assume that the regulator can make conditional regulations in the following sense: She offers (simultaneously) a separate contract to both the DSO and the DER. An accepted contract by one party is only valid if the other party also accepted his contract. Therefore, in the unconditional centralized solution, the losses due to acceptance by only one party do not occur.

The regulator therefore solves

$$\max_{x,y}\{(V-x-y)G(y)F(x)\}$$

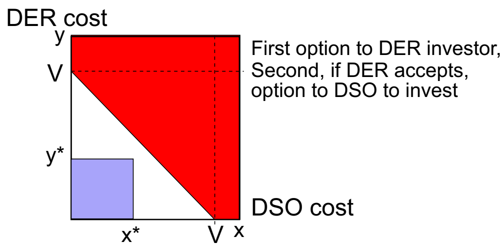

Fig. 6. DSO and DER investments, centralized conditional case, complements.

Table 1
Outcomes, uniform example, complements.

Regulation	z^*	$P(I,J)$	$E(W)$	Rationing	Misallocation	Single invest
First-best	1	0.500	0.167	No	No	No
Integrated	0.667	0.222	0.074	Yes	No	No
Centralized conditional	0.667	0.222	0.074	Yes	No	No
Decentralized	0.667	0.111	0.037	Yes	Yes	No
Centralized independent	0.000	0.000	0.000	Yes	Yes	Yes

Table 2
Outcomes, uniform example, substitutes.

Regulation	z^*	$P(I,J)$	$E(W)$	Rationing	Misallocation	Double invest
First-best	–	1.000	0.667	No	No	No
Integrated	0.354	0.583	0.376	Yes	No	No
Centralized conditional	0.500	0.750	0.417	Yes	No	No
Decentralized	0.451	0.575	0.316	Yes	Yes	No
Centralized independent	0.333	0.556	0.333	Yes	No	Yes

with corresponding first order conditions

$$x^*+y^* = V - \frac{F(x^*)}{f(x^*)}$$

$$x^*+y^* = V - \frac{G(y^*)}{g(y^*)}$$

This solution is illustrated in Fig. 6.

Example 4. For the case of $V=1$ and x, y following uniform distributions on [0,1], we obtain $x^*=y^*=\frac{1}{3}$. Investments take place with probability $\frac{1}{9}$ as in the decentralized regulation. The social loss corresponds to $\frac{7}{9} \simeq 78\%$ of the first-best investments.

We will shown some major differences between the different regulatory settings. In the first, the case of an integrated DSO–DER, we generally get the highest investment rates. The DSO internalizes the investment and the loss of investment is due to rationing by the regulator due to information problems. In the second scenario, where the DSO and DER are separate entities but the regulator delegates the contracting with the DER level to the DSO, we see lower investments and in particular a tendency to avoid investments with too high DER costs. Lastly, the third scenario with centralized contracting with the independent DSO and DER entities, the outcome depends on the complexity of the allowed contracts and in particular of the possibility to make conditional contracting. It is advantageous if the DER 'bid' can affect the DSO contract and vice versa so as to avoid the situation where only one party invests.

6. Conclusion

To summarize the findings, we table the outcome for the case of uniform costs [0,1] and welfare $V=1$, the situation for substitutes in Table 2 and for complements in Table 1, respectively.

For complements, the results in Table 1 show the social cost of decentralized schemes. Even for an integrated unit, the probability of investment is less than half of the social optimum. A centralized regulation can here replicate the second-best solution obtained from an integrated DSO internalizing all effects. However, a fully decentralized scheme leads to considerably lower investment level and misallocation of the investment opportunities. The worst outcome is found for the centralized independent regulation, where the regulator separately contracts with the two agents. Given a rational investment budget, this scheme does not lead to any investments at all.

For completeness, we also present the results for an identical application of the model for substitutes, see details in Agrell and Bogetoft (2011). Here, the centralized solution is the preferred option as it avoids misallocations (i.e., lowest cost investment is implemented) and does not involve useless duplicated investments. There is still losses associated with the outcome, namely due to the rationing. Rationing in the sense that not all investments with cost below the value to the consumers are undertaken is part of the solution since it enable the regulator acting as a substitute consumer to lower the information rents he has to pay.

If – for reasons that may go beyond the scope of the model – the two levels are separated (unbundled), we can foresee two possible organizations of the regulation. In the first, the regulator contracts with the DSO that has the option to outsource the investments. In the other, the DSO and DER are contracted individually by the regulator.

The best separated outcome is the first one, i.e. it involves decentralized regulation: only the DSO is contracted directly and the possible regulation of DER is delegated to the DSO. The advantage of this approach of having decentralized regulation of DER is that the DSO has private information about its own costs and that it can use this information when deciding how to incentivize DER. Nevertheless, this setting leads to less overall investment—at a higher cost to the consumers. Two types of inefficiencies are present, namely rationing and some misallocation of investment among the two levels. The DSO favors its own investments since outsourcing generates costs of asymmetric information.

When the regulator contracts directly with both levels, the outcome is less efficient—there will be rationing and double investments, i.e. in some cases, the DER and DSO levels will both end up investing even though this is unattractive since the investments are substitutes. This can be partly circumvented if the regulator uses conditional regulation such that the offer to one level depends on the response of the other level. The latter however may be a difficult approach in practice since it requires time to first offer the investment to a primary provider and next to a secondary provider if the primary provider declines.

In short, therefore, from the point of view of substitute investments, the regulator will prefer an integration of the DSO and DER activities—and if this is not possible, it would prefer a regulation of one of the levels leaving the control of the other to the directly regulated level.

Of course, this ranking of the different organizational and regulatory solutions may conflict with other objectives that we have ignored, including the need to incentivize cost reductions at the DSO level in general via relative performance evaluations like in a high powered revenue cap (CPI-X) regulation.

Taking the broader perspective, we provide two policy results, for the design of future incentive network regulation and for the organization of network services, respectively.

First, the results show that in the presence of increased importance for discrete delegated investments with high asymmetric information, the optimal regulation of future network services should remain a high-powered incentive regulation—with an inclusion of the investment driver as part of the service description of the DSO. An example of where this is used in yardstick design for electricity DSO is Bundesnetzagentur in Germany, cf. Agrell and Bogetoft (2007). The DEA frontier model specification used in the regulation includes variables for the subscribed capacity for decentralized generation into the network, divided by voltage level, as cost drivers.

Second, the network regulation should if possible be centralized to one agent with verifiable investments and no delegated or conditional rights. This means that the "negotiated agreements" are likely not a long-term solution for the network regulation in the future. This result can be directly compared to that of Joskow and Tirole (2005, Section 4) where the question of merchant investments in transmission can be delegated to the contracting parties, in their case two potential investors. For both complementary and substitute investments, the authors reject the applicability of the Coasian theorem (unless mitigated by long-term contracting) since a number of assumptions are not fulfilled; (low) transaction costs, complete information, presence of all stakeholders, absence of free-riding, absence of hold-up of potential losers. In the current situation, we note that several of these conditions are violated also in the case of the local DSO–DER bargaining. The DSO is naturally in informational advantage, there are high transaction costs involved to adequately describe and contract on the externalities involved on and off the grid, the future grid users are not represented at the negotiation although likely to assume the investment if made by the DSO, future investors in generation can free-ride on infrastructure in e.g. control equipment and protection etc. However, ownership unbundling has been a key policy objective in many European countries to promote competition amongst providers. In this paper we have shown an additional cost of unbundling, in the sense that unbundling leads more under investment in technologies that would impact climate change.

Finally, it should be noted that the discussion and the model is oriented to a specific policy issue: the provision of investment incentives for capital costs increases in order to accommodate and fully utilize the future smart grids. However, we note that the conclusions for our model are very timely also when it comes to the interface between TSOs and generators in the larger context of decarbonization of the energy system. An interesting example here is the treatment of hydro storage plants in Italy and Lithuania under an identical European regulation. Whereas the Italian regulator authorizes the TSO *Terna* to invest in, control and operate the storage facility, the Lithuanian TSO *Lietuvos Energija AB* was obliged to split off two similar pumped hydro-plants[20] in different interpretation of the directive. Seeing the investment in a pumped hydro-storage plant or in transmission network reinforcements necessary to transport energy from intermittent renewable energy resources far from the load as substitutes creates an additional illustration to our model. Either the operator integrate the benefits and costs, or the decentralized schemes would render the investment less likely, postponed or more costly. Alternatively, considering the investment in a pump storage at a specific site and the investment in specific reinforcements and control equipment at the TSO-level as complementary investments provide an illustration of the second case. Here again, the prospect that a regulated entity (here the TSO) were to tender off the construction and operation of a pump storage plant to independent generators at efficient cost is predicted to be an endeavour with low probability of success. Fundamentally, the smart-grid technology brings these kinds of trade-offs down from the transmission to the distribution system level, with an even higher incidence of investment decisions and subsequent social costs of delays, misallocation and duplication.

In the paper we have shown that – due to asymmetric information – regulation will always lead to a social loss. Unbundling between network and generation will add to this loss. However, in an unbundled situation – as is the norm in Europe – it is better to delegate the task of organizing and contracting the investments to the network operator than to regulate (or subsidize) the unbundled generator separately.

[20] Kaunas Hydro-Power Plant and Kruonis Pumped Storage Plant, Milciuviene and Tikniut (2009).

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